Advanced Finite Element Modeling Of Low Cycle Fatigue Crack Growth

WARP3D

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Overview

- Fracture Control Process
- Examples of Need
- Technical Approach Details
- Participants and Roles

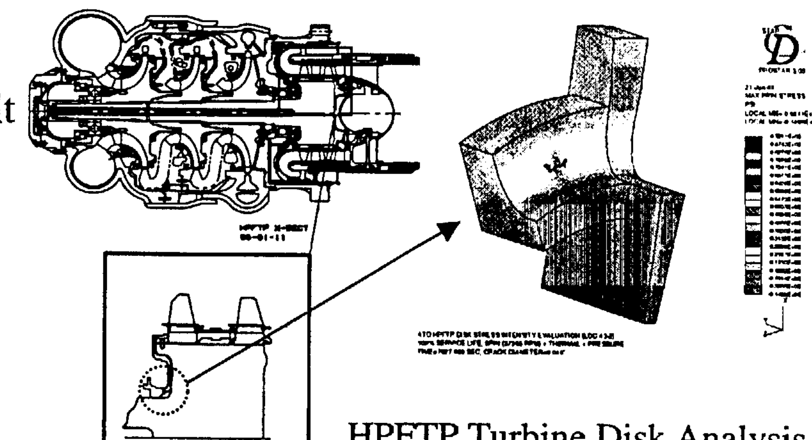
Overview

- Assumes a crack-like defect of a size which may be missed in inspection will exist in most critical location of any critical structure or component.
- Flaw existence assumption is usually, but not always, conservative based on past experiences in NASA and knowledge of manufacturing processes.
- Cyclic, environmental, and sustained loads used to generate stresses on models.
- Fracture Mechanics analysis used to predict crack growth and residual strength.
- Must show that defective structure will still provide four times required mission lifetime.
- Special exemptions cover redundant structures, low risk parts, etc.
- Assessments require specialized software tools, experienced analysts, and reliable material crack growth rate test database.

Current Example of Advanced LCF Fracture Analysis Need

- Pratt & Whitney High Pressure Fuel Turbopump (HPFTP): Turbine housing cracking problem in stress concentrations
  - H2 "steam" 300F environment results in unexpected time dependent crack growth in IN100 material
  - Regions of high stress and localized yielding currently result in cracking
  - Life prediction difficult due to plasticity and combined da/dt and da/dN behavior

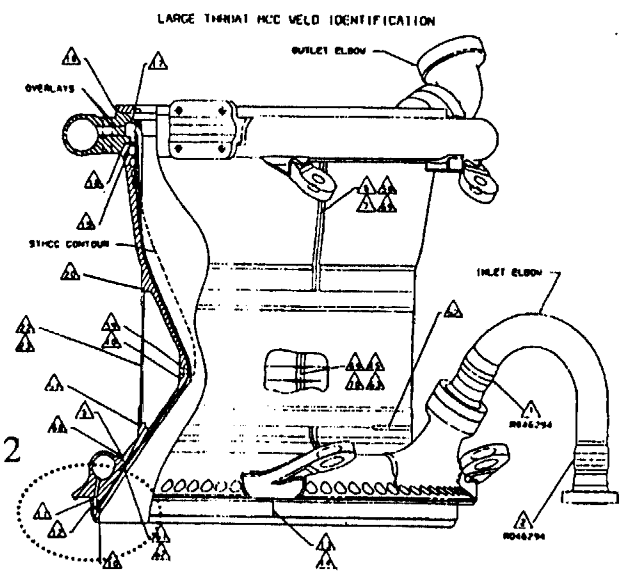
- HPFTP Turbine Disk: Also IN100
  - High stresses and regions of localized yielding combined with the hydrogen environment result in extremely small critical initial flaw sizes predicted by LEFM analysis
  - Requires extraordinary NDE to meet fracture control - very costly
  - Considerable expense and effort to produce even the limited LEFM analysis



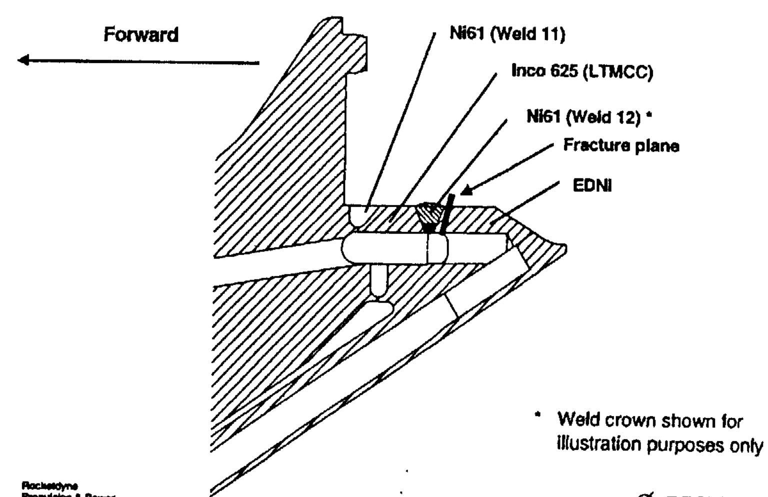
HPFTP Turbine Disk Analysis
Pratt & Whitney

Current Example of Advanced LCF Fracture Analysis Need

- SSME Large Throat Main Combustion Chamber (LTMCC)
  - Weld cracking due to liquid metal embrittlement during welding
  - Welding electro-deposited nickel with sulfur contamination has produced hardware with cracks at weld joint 12
  - Current fracture life analysis tools are unable to accurately analyze LCF life of assumed defects. Currently flying on risk assessment and fleet leader
  - Fracture analysis of Weld 12 cracking involves multiple materials, residual stresses, thermal loads and plastic material behavior



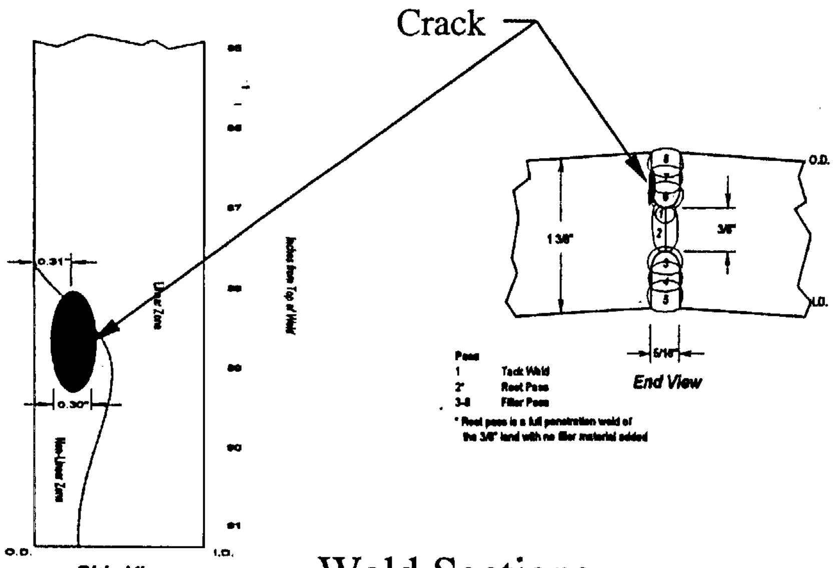
SSME Large Throat Main Combustion Chamber



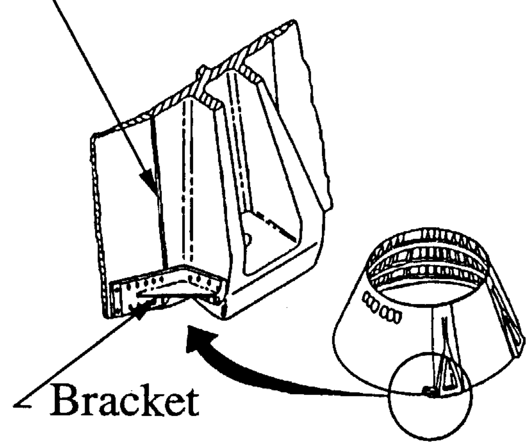
Historical Example of Advanced LCF Analysis Need: Solid Rocket Booster

Fracture Mechanics Tool Development
MSFC Engineering Directorate
ARC, LaRC,, UIUC, STANFORD

- SRB Aft Skirt Hold-Down Post
  - Nondestructive evaluation of weld indicated embedded defect near the edge of the critical weld at the hold-down post.
  - Launch stresses in vicinity of defect exceed the tensile yield stress of the material.
  - Abort event cyclic stresses exceed tensile yield and compressive yield.
  - LEFM analysis not valid in region of defects.
  - Stiffener bracket added to reduce stresses in weld to a point where LEFM could be applied for safe-life analysis.
  - Verified tool for LCF crack growth analysis would likely have predicted adequate life and precluded the need for the stiffener bracket



Weld Sections



Aft Skirt

Project Technical Goals
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Provide MSFC and the Agency with an Advanced Modeling and Simulation Capability for LCF Assessments of Fracture Critical Components

- Adopt SwRI and Rocketdyne framework as starting point for all new work
    - Builds on advanced fracture methodology work sponsored by MSFC
- Extend applicability/validity of ΔJ_{eff} approach through advanced micro-mechanical models & fracture concepts
- Implement LCF simulation capabilities into the highly parallel, WARP3D Code
- Improve usability aspects of WARP3D for LCF assessments of complex, 3-dimensional geometries & loading histories
- Maintain the momentum in WARP3D development and improve collaborative research across NASA Centers and academia

Fracture Mechanics Tool Development
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ΔJ_{eff} Approach for LCF Assessments

- Simulations of cyclic, thermo-mechanical loading of complex, 3-D components containing cracks
- ΔJ Solutions extracted from 3-D simulations
- Direct computation of closure levels ($\Delta J \rightarrow \Delta J_{\text{eff}}$) in the 3-D models
- Transferability of model parameters, $da/dN(\Delta J_{\text{eff}})$, from lab tests to actual components (SSY →LSY to include strong constraint effects)
- Environmental effects on da/dN

Addresses specific recommendations for new work in SwRI & Rocketdyne studies

Technical Approach
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ΔJ_{SSY}-ΔJ_{LSY} Correlation

- Use micro-mechanical models that describe d*a*/d*N* in terms of cyclic, crack front σ-ε fields, $da/dN = \Phi\ (\sigma, \varepsilon, \text{material props}, \ldots)$
  - Some early fundamentals expected to be supported by the "Design for Safety" program out of ARC. Consortium approach - MSFC MP&M involved
- Use finite element analyses to couple ΔJ_{SSY} and ΔJ_{LSY} values which generate same $\Phi(\ )$
  - Area of research with heaviest MSFC technical involvement
- Initial work to use $\Phi = \Phi\ (\Delta W_p + \Delta W_e)$* From D. Nelson's most recent work* for multi-axial LCF (Including In 718)
- Environmental effects increase Φ (e.g. Hydrogen)
- This procedure extends the successful approach developed by Dodds, *et al.* to model constraint effects on fracture

***Park, J., & Nelson, D. Evaluation of an Energy-Based Approach and a Critical Plane Approach for Predicting Constant Amplitude Multiaxial Fatigue Life. To Appear in *Int. J. Fatigue*, 2000.**

Technical Approach
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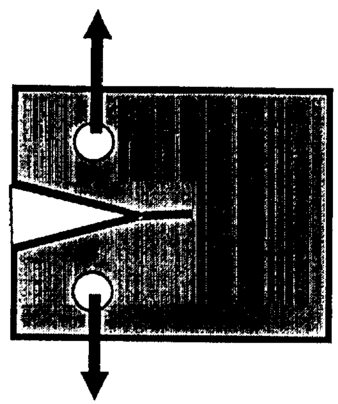
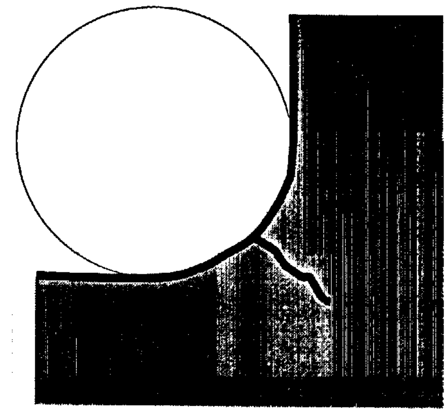
Key Issue: LSY-SSY Transferability





$$\left(\frac{da}{dN}\right)_{test} = C(\Delta J_{eff})^m$$

$$\left(\frac{da}{dN}\right)_{component} = C(\Delta J_{eff})^m$$

But, tests show: $\left(\frac{da}{dN}\right)_{test} \neq \left(\frac{da}{dN}\right)_{component}$

Because ΔJ_{eff} does Not generate same near-front stress-strain fields in the two conditions

Technical Approach
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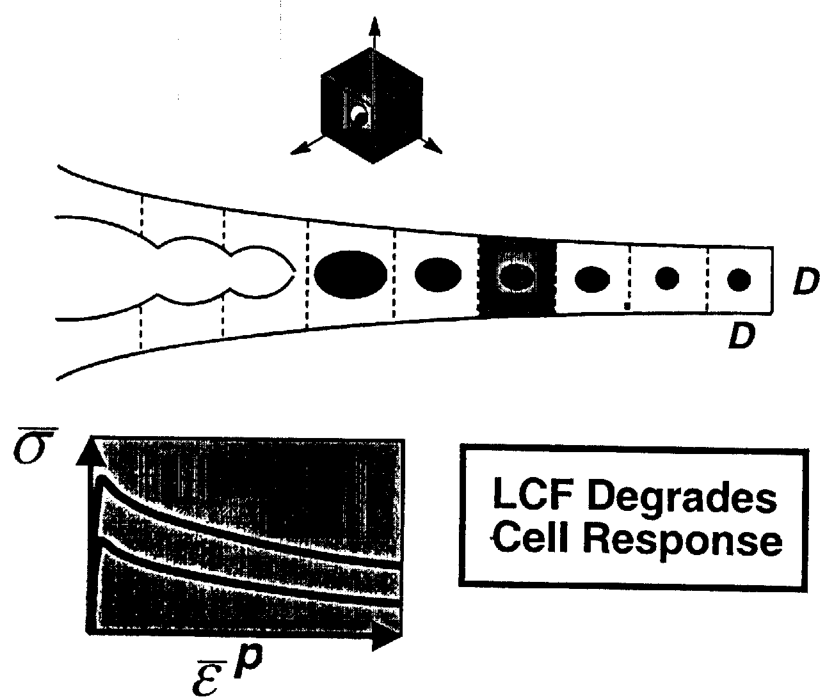
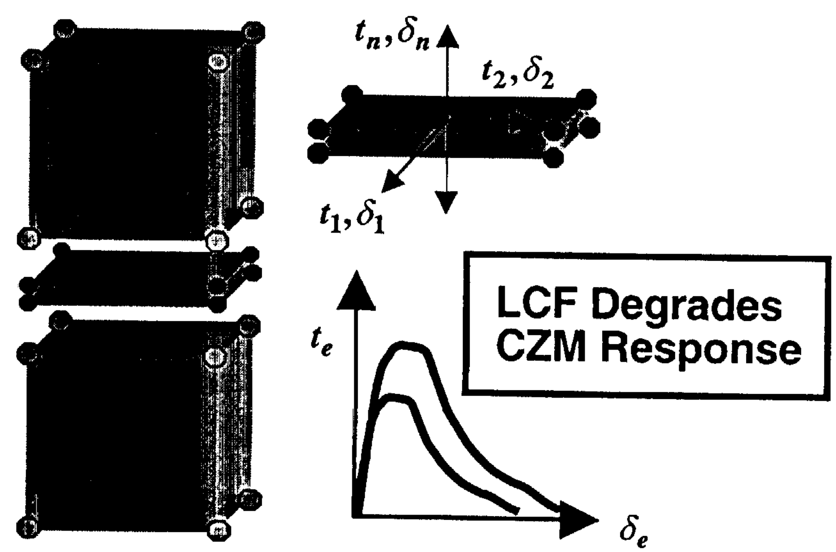
Advanced Work Under Consideration

- **Growing Cracks Due to LCF in Full 3-D Analyses**
  - **Modify Cohesive Zone Models to Degrade Cohesive Properties Due to LCF Induced Material Damage**
  - **Extend Cell Methodology to Incorporate a Failure Criteria Based on LCF Induced Material Damage**





New WARP3D Capabilities for LCF

- New Cyclic Plasticity Models, ΔJ, and 3-D Contact
- Usability Enhancements
  - Improved interface to specialized crack model generators
  - Improved interface to-from Patran and WARP3D
  - Automatic solution procedures to drive execution of LCF analyses
- Library of Standard 3-D Models for LCF Studies
  - Lab test specimens: SE(B), C(T)
  - Common 3-D geometries (e.g. surface cracks plates, pipes, elbows)

Participants

- NASA-MSFC
  - Doug Wells / ED33*
  - Wayne Gregg / ED22*
  - Preston McGill / ED33*
  - Greg Swanson / ED22*‡
  - Ken Swaim / ED22*
- NASA-AMES
  - Roy Hampton‡
- NASA-Langley
  - Jim Newman‡
- NASA-JSC
  - Royce Forman‡

* MSFC Fracture Control Board
‡ NASA Fracture Control Methodology Panel

- University of Illinois (UIUC)
  - Prof. Bob Dodds
  - Prof. Keith Hjelmstad
  - Prof. Petros Sofronis
  - Post-Doc Researchers
  - PhD Students
- Stanford University
  - Prof. Drew Nelson (Project Consultant)
- SwRI Collaborative Efforts (NASGRO)
  - R. Craig McClung
  - Graham Chell
  - Yi - Der Lee

Participants & Roles
WARP3D Development

MSFC: Project direction: Engineering Directorate lead with MSFC Fracture Control Board participation -- a new MSFC FCB activity

- Maintain focus on Center needs, material testing and FE analysis supporting code development and verification

ARC: Project advising

- Roy Hampton- NASA Fracture Control Methodology Panel, Primary NASA technical advisor to WARP3D development over past 4 years

LaRC: Project consulting

- Jim C. Newman- Recognized as the Agency-wide expert in fracture mechanics

UIUC: Project theoretical development and coding

- Prof. Bob Dodds, Civil Engineering- Leader of WARP3D Development, Editor: *Engineering Fracture Mechanics*, recognized authority in computational fracture mechanics
- Prof. Keith Hjelmstad, Civil Engineering- expertise in cyclic plasticity and parameter estimation
- Prof. Petros Sofronis, Theoretical and Applied Mechanics- expertise in continuum models of hydrogen effects on metals

Stanford: Project consulting

- Prof. Drew Nelson, Mechanical Engineering- expertise in modeling and prediction of low cycle and multi-axial fatigue

Participants & Roles
WARP3D Development

Research Team Collaboration

- Technical Interchange Meetings for entire research team
- Regular Visits from UIUC at MSFC for Collaborations, Technical and Training Seminars
- Exchange Visits from UIUC of 2-3 Days During Academic Year
  - NASA people should visit UIUC as well
- Extended Summer Visits at NASA centers by Faculty, Post-Doc and PhD Students
- Updating & Direct Support for Development Versions of WARP3D Code, Mesh Generators on NASA Computers
- Assistance in Use of WARP3D and Mesh Generators to Perform LCF and Other Fracture Simulations